# DEVELOPING RESISTANT PLANTS – The Ideal Method of Controlling Insects



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## Contents




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# Developing Resistant Plants – The Ideal Method of Controlling Insects

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The most effective and ideal method of combating insects that attack plants is to grow insect-resistant varieties.

E. F. Knipling, U.S. Department of Agriculture, and others have placed much emphasis on the need for nonchemical control of insect pests. The late Rachel Carson in her controversial book, "Silent Spring," emphasized the hazards to man and animals of using chemical pesticides and encouraged the development of other methods for controlling insects. Some of the alternatives she mentioned, which have been investigated for many years by entomologists, include (1) using biological control agents, that is, releasing insects and diseases that kill destructive insects of economic importance; (2) using attractants to lure insects to their death; (3) treatment with radiation or chemosterilants to sterilize either one of a mating pair so the resulting eggs are infertile; and (4) applying electromagnetic energy, that is, destroying insects by using light or sound in some manner.

Miss Carson did not mention the development of plants with natural resistance as a method, perhaps because it is a hidden control. Natural resistance is one of the safest, most practical, and at the same time one of the most economical approaches to biological control yet conceived. Indeed, the potential of this method of controlling insect pests staggers the imagination.

What is an insect-resistant plant? A plant has a degree of resistance to insect attack if it sustains less damage at a given level of infestation than the average of other plants grown in the same environment. The reasons a plant is resistant are usually complex, and they vary depending on the insect and the crop. The late R. H. Painter of Kansas State University was an internationally known authority on host plant resistance to insect attack. In his book "Insect Resistance in Crop Plants," he suggested that three interrelated factors affect resistance: (1) Plants may not be acceptable to the insect as food, oviposition site, or shelter. (2) Plants may adversely affect development of the insect, and feeding on them may kill the insect (this is called antibiosis). (3) Plants may be tolerant to insect attack, that is, they may show less damage than susceptible plants or may survive infestations that would severely injure or kill more susceptible plants.

How is a resistant variety obtained? Scientists use three general methods: (1) They introduce a variety that through natural selection already possesses a higher-than-usual level of resistance to a given pest. (2) They expose plants of a given variety to pests and select the resistant individual plants for propagation. (3) They hybridize plants to transfer the demonstrated resistant characteristics or germ plasm to desirable varieties.

Scientists have known for many years that plants and animals differ in their response to the stresses and strains of their environment. Some individuals within the same species or strain are resistant to insects, diseases, and an adverse environment; others are susceptible. Also, when conditions are adverse, according to Darwin's law of survival of the fittest, many individual plants and animals are eliminated from the environment; others survive and perpetuate their kind. Those that survive as a group are then more resistant to the specific environmental hazard than were their parents. This process of natural selection is constantly at work. If nature had been left undisturbed by man from the beginning so that plants had been allowed to develop in a completely wild environment, many species would undoubtedly have evolved with some resistance to insects and diseases.

W. H. Skrdla of the U.S. Department of Agriculture noted that such a resistant wild species actually evolved in the tomato family. Some years ago when scientists were studying plants in Peru, where the tomato originated, they found a wild tomato plant growing in a sugarcane field. This plant, now called the Trujillo tomato, was nearly immune to the diseases caused by the organisms *Fusarium* and *Alternaria* spp.

The environmental factors that caused such a plant to evolve are not known. Perhaps it was the lone survivor of many attacked by *Fusarium*, *Alternaria*, or similar organism. Perhaps it was the only one that survived stress factors other than disease that were present in the environment. Regardless of the nature of the resistance and how it was formed, the resistant germ plasm in this one tomato plant has been a blessing to the American farmer. From the one source of resistance, more than 30 commercial varieties of tomatoes have been developed. How many wild plants of other culti-

vated crops contain germ plasm that is resistant to disease or insects or both and are growing isolated and unrecognized in their country of origin?

In agriculture today, natural selection is seldom allowed to take place. Man persists in moving plants from place to place so they are exposed to new pest species. Man also is responsible for spreading insects and diseases into new areas before the native plants can develop resistance. Moreover, natural selection and development of resistance to pests, according to Darwin's law of survival of the fittest, do not necessarily assure the evolution of plant varieties that provide the food, fiber, or esthetic features that man may require or desire in a plant variety. Generally the plants that survive pressures, though they possess some resistance to stress factors such as insects, diseases, and drought, usually have few desirable agronomic characteristics. For example, the monococcum group of wheats possesses some resistance to the wheat stem sawfly (*Cephus cinctus* Norton) and to the Hessian fly (*Mayetiola destructor* (Say)) but has few, if any, desirable characteristics from the standpoint of agronomy or food.

Agricultural scientists, therefore, have had to assume the part once taken by nature in breeding and developing plant varieties. In a few years they try to breed selections that might take nature hundreds or even thousands of years to develop. Working in their experimental nurseries, they use sophisticated techniques of breeding and cell analysis. However, they place primary emphasis on plant varieties with desirable agronomic characteristics. Previously they had given scant attention to qualities that render a plant resistant to insects, primarily because most breeders do not have available the necessary insect populations or techniques to test the plants for resistance or susceptibility. As a result, many varieties grown today are acceptable agronomically but have little or no built-in resistance to insects.

The urgent need to find methods other than chemical to control insect pests has now prompted scientists to place increased emphasis on the breeding and development of varieties with insect resistance. The primary goal of this research is to find, identify, and transfer natural insect resistance into plants being developed for commercial production. This research has been very successful. Scientists have found sources of insect-resistant germ plasm, have bred this resistance into commercially acceptable varieties, and have released these resistant plants to farmers.

The impact of this remarkable method of insect control on American agriculture can best be understood by noting a few of the many outstanding accomplishments obtained by using varieties with built-in resistance to insect attack.

## Hessian Fly

The Hessian fly, a black gnatlike insect one-fourth inch long, lays eggs on leaves of wheat plants. Maggots hatching from these eggs kill the wheat by sucking the plant juices. At one time the Hessian fly was considered the most serious pest of wheat in the United States and caused annual losses of millions of dollars. Today such losses are comparatively minor. Rarely, if ever, do Hessian flies destroy an entire field.

The dramatic shift in the economic importance of the Hessian fly was due largely to the development of insect-resistant wheat varieties (fig. 1).

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FIGURE 1.—Hessian fly damage in (fall) winter wheat at Lafayette, Ind. Standing rows are W-38 resistant; other rows are susceptible varieties.

Also delaying the seeding of wheat in the fall until most of the fall brood of flies disappeared helped reduce populations. One of the first varieties resistant to the Hessian fly was Pawnee, a hard red winter wheat released in 1942. Twenty-two other varieties with resistance to the Hessian fly are now available: Gage, Omaha, Ottawa, Ponca, Warrior (hard red winter wheats); Ace, Arthur, Benhur, Dual, Georgia 1123, Knox 62, Monon, Redcoat, Reed, Riley, Riley 67, and Todd (soft red winter wheats); Big Club 43 and Poso 42 (soft white spring wheats); and Lathrop, Parker, and Russell (hard red spring wheats).

Many State experiment stations are so convinced of the value of built-in insect resistance that they no longer release a new wheat variety unless it is resistant to the Hessian fly in its genetic makeup.

As an example of the economic importance of wheat varieties resistant to the Hessian fly, let us consider the results of two studies. R. L. Gallun, entomologist, U.S. Department of Agriculture, in cooperation with plant scientists from the various

States conducted a survey, which indicated that $8\frac{1}{2}$ million acres of wheat resistant to the Hessian fly were grown during 1964. R. H. Painter in 1942 estimated that the Pawnee variety yielded about 14 bushels per acre more wheat when the Hessian fly infestation was heavy than did the susceptible Tenmarq. (Heavy infestations of this fly have been known to destroy an entire crop.) If we assume that farmers are growing wheat resistant to the Hessian fly because the infestation is heavy and that the fly can damage and reduce yields by as much as 14 bushels per acre, the growing of resistant rather than susceptible varieties in 1964 prevented a loss of 119 million bushels of grain valued at about $238 million. This loss is probably excessive, because heavy infestations of the Hessian fly would probably not prevail throughout the entire $8\frac{1}{2}$ million acres of resistant wheat planted. However, even if infestations were light and spotty, the savings to the grower would certainly have to be estimated at half this amount or $119 million.

Growing wheat varieties resistant to the Hessian fly is so effective in some areas that reduced infestations approach eradication. After Big Club 43 and Poso 42 were released in California, W. B. Noble, formerly of the U.S. Department of Agriculture, reported in 1950 that as the acreage of these two wheats increased, the fly population decrease was such that the insect forms were difficult to find. Less than 1 percent of the wheat grown in California's Butte and Solano Counties was infested with the Hessian fly, where previously it had been heavily infested. Thus the Hessian fly is no longer a problem in this area of California, even though susceptible wheats are again grown widely.

According to R. H. Painter, a similar situation prevailed in central Kansas just after Pawnee was released.

The successes indicate that populations of the Hessian fly could probably be reduced to minimum levels throughout all infested areas of the United States if the entire wheat acreage were seeded exclusively to resistant varieties.

The reader may then conclude that the Hessian fly is no longer a problem. Unfortunately this is not so. Although planting varieties resistant to insect attack effectively controls the biological forms of this fly in most fields today, these same varieties will not necessarily eliminate the biological forms that may appear tomorrow. Like all living creatures, the Hessian fly in most areas of the country is constantly changing biologically, and it is therefore adjusting to the types of plants now grown within its environment. Its adjustments require a compensating adjustment in resistance of the wheat plant.

W. B. Cartwright, W. B. Noble, and R. L. Gallun of the U.S. Department of Agriculture and other scientists have demonstrated that biological strains of the Hessian fly can successfully attack some resistant wheat varieties now in commercial production (fig. 2). Dr. Gallun reported four such


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FIGURE 2.—Hessian fly biological race A developed on susceptible wheat variety Michigan Amber but not on resistant wheats Dual, Purdue 39153, and Purdue 4217.

biological races in Indiana, designated for experiment purposes as races A, B, C, and D. Each was selected from samples of the native field population of the State, and each race was identified on the basis of the insect's ability to infest and reproduce successfully on varieties of wheat with different types of resistance to the Hessian fly.

In the past, biological race A has predominated in wheatfields in Indiana. However, during 1955–65 as the acreage planted to varieties resistant to race A (Dual, Monon, Redcoat, and Reed) increased, populations of race A declined or disappeared in some areas. Race B, which can survive on these varieties, has now become dominant. Fortunately scientists anticipated this change and developed Benhur and Knox 62, which are resistant to this race. These varieties are now being introduced into areas infested with race B.

Growing Benhur, Knox 62, or any other wheat with resistance to one or possibly two biological races will not permanently solve the problem of the Hessian fly. To be really effective, a variety should be resistant to all known races. Experimental multirace-resistant varieties have already been developed and will soon be ready for the farmer. It is only through such a continuing research program that scientists will be able to control the ever-shifting complex of Hessian fly races found throughout the wheat-growing areas of the United States.

## Wheat Stem Sawfly

The wheat stem sawfly is a pest of primary economic importance to wheat growers throughout the Great Plains area of western Canada and the United States. In 1941 the late C. W. Farstad of the Canadian Department of Agriculture estimated that wheat losses caused by the sawfly in Canada amounted to several million bushels annually. In some fields losses ranged from 75 to 85 percent. The North Dakota Department of Agriculture estimated that losses for the State in 1944 approached 3 million bushels of grain valued at about $6 million.

The adult sawfly is a black wasplike insect about one-fourth to one-half inch long. However, it is the larva, which is cream colored, black headed, and about one-half inch long, that causes damage by boring up and down inside the wheat stem and cutting it at the base as the plant matures.

Control of the sawfly is complicated because the insect spends most of its life cycle—from egg to adult—within the wheat stem. Most insecticides do not control the sawfly, but certain cultural practices reduce damage. These practices include rotating the wheat crop with oats and barley, planting nonpreferred host plants in or near infested fields, shallow plowing to expose infested overwintering stubble to the weather, and early harvesting or swathing to remove the grain from the field before it is damaged. However, the most effective control is to grow wheat varieties resistant to sawfly attack.

The story behind the development of Rescue, the first sawfly-resistant wheat, and the manner in which this variety reduced sawfly populations in Montana from epidemic to minimum numbers in only a few years reads like a melodrama. It might well be entitled, "Rescue to the Rescue."

As early as 1920, the wheat stem sawfly was a serious pest of wheat in Canada. In 1924 researchers began to look for a satisfactory control method. They tried biological control, insecticides, and cultural practices. None of these methods, which are usually effective in controlling other insect pests, were entirely satisfactory. Just when it appeared that no satisfactory control could be found, C. W. Farstad, entomologist, and A. W. Platt, agronomist, Canadian Department of Agriculture, working as a research team in Alberta, Canada, noticed that solid-stemmed wheat suffered less damage than hollow-stemmed wheat because the sawfly larva could not complete its development in the solid-stemmed plants. The pith in this wheat provided a mechanical barrier to the feeding and movement of the insect within the stem. This observation proved to be the key to developing varieties resistant to sawflies.

One group of solid-stemmed wheats from Portugal, originally developed to resist lodging along the windy coastal area of this country, was especially resistant to the wheat stem sawfly. Farstad and Platt crossed one of these varieties (S–615) with the variety Apex, a commercial Canadian wheat of high quality and yield. From the progeny of this cross they developed the first wheat variety resistant to the sawfly and appropriately named it Rescue. Rescue proved to be effective in reducing grain losses caused by the sawfly. When it was planted in experimental nurseries at several locations in Montana and Canada, the cutting damage by the sawfly was less than 10 percent in the solid-stemmed variety but as high as 90 percent in the hollow-stemmed variety Thatcher (fig. 3). Therefore in the fall of 1944 when control became unusually urgent, an immediate increase was planned in the small amount of experimental Rescue seed available.

One bushel of Rescue seed was given to the United States in October 1944. The Montana Agricultural Experiment Station and the extension service reported that this 1 bushel was increased to 60,000 bushels in only 24 months. This 1 bushel of seed was shipped to the Arizona Agricultural Experiment Station for planting during the winter of 1944–45. By the spring of 1945, 35 bushels of Rescue seed were sent to and planted

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FIGURE 3.—Wheat stem sawfly cutting damage in heavily infested spring wheat: Left, solid-stemmed, resistant Rescue; right, hollow-stemmed, susceptible Thatcher. (Courtesy of Raymond Kelly, Choteau, Mont.)

by the Montana Agricultural Experiment Station. In the fall of 1945, 877 bushels of seed were harvested. These 877 bushels were then shipped to Arizona. In the spring of 1946, 3,870 bushels of seed were harvested and sent to Montana. The train carrying the seed was delayed by a railroad strike, but special authorization was obtained from railroad and labor officials to permit the shipment to proceed. At each designated dispersal point in the infested area, Rescue seed was rationed to farmers as if it were gold. Less than 24 hours after delivery, all the seed had been planted, but planting was at least a month later than usual for this area. As if by a miracle, rain fell soon afterward, and an excellent crop of about 60,000 bushels of grain was obtained in the fall of 1946. By the end of the 1947 season enough Rescue seed was available to plant all the sawfly-infested acreage in Montana. In 1948 the losses due to sawfly damage declined an estimated $4 million. In the following years sawfly populations and wheat losses were reduced to a minimum in all areas where Rescue was grown.

It is difficult to estimate the value of that original bushel of Rescue seed to the Montana farmer. Its development cost only a few thousand dollars for the salaries of a part-time plant breeder and entomologist. Any estimate of the value would probably be too low. However, scientists in this country would have taken at least 10 years to develop a resistant wheat variety similar to Rescue. Also, losses from sawfly damage dropped an estimated $4 million the first year Rescue was widely grown. Thus a conservative estimate for a 10-year period would be that the 1 bushel of wheat saved Montana farmers at least $40 million, and savings to the Canadian farmers were probably many times this amount.

The value of Rescue cannot be measured entirely in terms of dollars saved by preventing damage. Like Hessian fly-resistant wheats, Rescue is also efficient in suppressing sawfly populations. Scientists have observed many times that when Rescue has been grown for 5 or 6 successive years in a field or area, sawfly populations are reduced to such a low level that susceptible varieties can again be grown for several years without damage. However, also like the Hessian fly-resistant wheats, Rescue did not completely solve the sawfly problem. For all its hardiness, Rescue has some undesirable agronomic characteristics. Too, it is not rust resistant and cannot be used in North Dakota and eastern Montana, where both the wheat stem sawfly and rust are serious problems. After the release of Rescue, American and Canadian scientists coordinated their research to develop resistant wheats for all areas infested with sawflies and rust.

Some spring wheat varieties developed by this cooperative research program were Chinook and Cypress from Canada and Sawtana and Fortuna from the United States. The development and release of Fortuna by K. Lebsock and W. B. Noble of the U.S. Department of Agriculture and by the North Dakota Agricultural Experiment Station in 1966 is a milestone, since this is the first variety to have both sawfly and rust resistance. Researchers also developed resistant winter wheats. Rego, a hard red winter wheat resistant to the sawfly, was the first of its kind. The credit for its development goes to E. R. Hehn and C. R. Haun of the Montana Agricultural Experiment Station and F. H. McNeal and P. Luginbill, Jr., of the U.S. Department of Agriculture. Other experimental spring and winter wheat selections with improved resistance to sawflies and rust are in the final stages of testing.

The success of past research efforts in developing agronomically acceptable wheats with good sawfly and rust resistance indicates that perhaps in 5 or at most 10 years resistant varieties will be available for all areas where the sawfly is a problem. The farmer can then control this insect by simply planting the resistant variety recommended for his area.

## Spotted Alfalfa Aphid

The spotted alfalfa aphid (*Therioaphis maculata* (Buckton)) is soft bodied, about one-sixteenth inch long, and straw colored except for six or more rows of dark spots along its back. Both the nymphs and adults suck the juice from leaves or stems of alfalfa and thus reduce stands, lower yields, and increase harvesting costs. This pest was first discovered in southeastern New Mexico early in 1954. It spread rapidly the next 2 years into

30 States across the southern two-thirds of the United States. Damage during 1954–56 was estimated at $81 million.

Soon after its discovery, researchers began to look for a satisfactory method of control. They tried biological control, insecticides, and alfalfa varieties resistant to the aphid. The most successful method was using resistant varieties.

In 1955 State and Federal entomologists and plant breeders, working in teams, began to locate sources of germ plasm that were resistant to the spotted alfalfa aphid. They used this germ plasm to develop resistant varieties that could be adapted to various alfalfa-growing areas. Almost immediately they found that the variety Lahontan was resistant to the aphid. Lahontan was originally developed for resistance to the stem nematode (*Ditylenchus dipsaci* (Kühn)). This resistance to two plant pests was fortunate. Not only did the farmer now have a readily available and efficient method of combating the aphid, but also the entomologist and plant breeder had a valuable germ plasm that could be used to develop other resistant varieties. Unfortunately Lahontan, though highly resistant to the aphid, is only moderately hardy in cold weather and is not adapted to some areas in the extreme Southwest where the aphid is most abundant.

In 1955 a team of Federal and State scientists began a crash program to develop a resistant variety that would meet all the requirements. They searched for resistant plants of African alfalfa, the variety most commonly grown in the Southwest. After much testing and selecting, they located seven clones from Nevada and two from California. From these they developed a new synthetic variety, Moapa, and released it to the growers in 1957. Moapa, in addition to having all the desirable agronomic qualities of the African varieties, was also aphid resistant. Its development and release in 3 years (1955–57) was a remarkable accomplishment, since a new variety usually takes about 10 years to develop.

Subsequently scientists have developed many more resistant varieties. Zia, adapted to New Mexico and parts of Texas, was released in 1958. Cody was released in 1959. It was developed for Kansas and adjacent areas where more than 3 million acres of Buffalo, an aphid-susceptible variety, were formerly grown. Sonora, adapted to Arizona, Nevada, and California, was released in 1963. In 1963 the total land planted to these five varieties was estimated at 1,700,000 acres, and scientists conducting tests in Arizona found that damage in fields planted to susceptible varieties was more than 20 times that in fields planted to resistant varieties. Also at Bakersfield, Calif., large-scale plots were seeded with Moapa and Lahontan and with several susceptible varieties (fig. 4). The results indicated that the resistant varieties outyielded the susceptible by as much as 50 percent.

Thus the annual savings to the grower in dollars must run into millions. For example, nearly 2 million acres of resistant varieties were planted in 1963. The yield on irrigated, suitable land should be about 2 tons per acre. Then since heavy aphid populations throughout this area could reduce the yield 50 percent and since top-quality hay sells for about $35 a ton, the savings for 1963, based on yield alone, could have been $70 million. These loss estimates are probably excessive, because heavy aphid infestations would most likely not occur throughout the entire area planted to resistant varieties. However, even if infestations were light and spotty, the annual savings to the growers would certainly have to be estimated at half this amount or a conservative $35 million.

Perhaps the most amazing aspect of developing varieties resistant to the spotted alfalfa aphid was the low cost. C. H. Hanson of the U.S. Department of Agriculture wrote in the May 1961 issue of "Crops and Soils" that he estimated the cost of de-

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FIGURE 4.—Spotted alfalfa aphid damage in alfalfa varieties at Bakersfield, Calif.: Susceptible Calverde and Arhims (rows killed) and resistant Moapa and Lahontan (uninjured rows).

veloping Moapa to be less than $30,000, the amount paid in salaries to part-time plant breeders and entomologists.

Researchers must continue to develop new alfalfa varieties that are resistant to aphid attack and adaptable to all areas of the country where the spotted alfalfa aphid is a problem. They must also constantly search for insect biotypes, since it is always possible that a biologically different strain will develop in nature that might successfully attack and reproduce on resistant varieties. In California several years ago aphids that appeared to be a biotype developed on one of the parent clones of Moapa growing in a nursery. Although this biotype has not become established in the field and on Moapa, researchers are already trying to find resistant clones that can be substituted for susceptible ones if necessary.

What about other insects that attack alfalfa? Scientists have begun to develop synthetics (varieties) with some degree of resistance to such other major insect pests as lygus bugs (*Lygus* spp.), the clover seed chalcid (*Bruchophagus roddi* Gussakovskii), the alfalfa weevil (*Hypera postica* (Gyllenhal)), the meadow spittlebug (*Philaenus spumarius* (L.)), the potato leafhopper (*Empoasca fabae* (Harris)), and the pea aphid (*Acyrthosiphon pisum* (Harris)). Team, a new high-yielding alfalfa variety with resistance to the alfalfa weevil, pea aphid, and several plant diseases, is a product of this research. Its name honors the cooperative efforts of the Agricultural Research Service and the agricultural experiment stations of Maryland, North Carolina, and other States. The ultimate goal is to provide synthetics with resistance to all major insect pests of alfalfa.

## European Corn Borer

The European corn borer (*Ostrinia nubilalis* (Hübner)) is the most destructive insect pest of corn in the United States. In 1949 alone it caused damage estimated at $350 million.

The borers, believed to have been introduced in broomcorn from Hungary or Italy, were first observed in this country in 1917. Since then the insect has spread rapidly and is now found throughout the corn-growing areas of the United States.

Like many insects, the European corn borer has four stages of development—egg, larva (caterpillar), pupa, and adult (moth). It overwinters as a larva, usually in the cornstalk, changes to a pupa in May, and emerges as a moth from late May to July. The adult moth deposits eggs in irregular white clusters on the underside of corn leaves. They hatch in 5 to 7 days, and the young larvae emerge. They work inside the cornstalk, where they cannot be reached by chemical or other control agents. Here they destroy the food channel of the plant. The resulting plant starvation causes incomplete development of ears and weakens the stalk or ear shank. Eggs of the second brood of borers are laid between July and September and the larvae appear from August through late October.

We have four ways to control this pest. The recommended cultural practices include feeding infested plants to livestock and plowing under the corn so that the adult moth cannot emerge. Insecticides can be used. Insect parasites and diseases can be released to destroy the borer. Corn can be grown that has built-in immunity or resistance to the borer.

The most promising control method is using resistant hybrids. The search for such varieties really began when hybrid corn was introduced, because with open-pollinated corn, borer resistance was difficult to obtain without losing some of the many good agronomic qualities. Also, it was difficult to incorporate insect resistance in open-pollinated corn. However, with hybrid corn, resistance could be rapidly and easily incorporated from one or several resistant inbreds.

The term "resistant" applied to plants attacked by the European corn borer means possessing qualities that inhibit the borer's establishment and survival in or on the plant. Against very young larvae, this type of resistance has its chief effect during the whorl stage of plant growth, when the larvae become established and feed primarily in the whorl. Resistance to feeding on leaves in this area of the plant is usually associated with first-generation corn borers. Inbred lines with high resistance to such first-brood infestations have been released from several State experiment stations. Some inbred lines contributing resistance to hybrids are A392, B2, L317, Oh7, Oh40B, Oh41, Oh43, Oh45, Oh51A, R4, R61, W10, W22, W23, and WR3. (The number of resistant lines in a hybrid determines its level of resistance. For effective resistance, a hybrid should contain at least three.)

The term "tolerance" is usually applied to resistance associated with infestation by the second-generation brood. A line or hybrid with borer tolerance is one that stands up well to infestation, has no shank breakage, and the corn can be harvested efficiently with mechanical equipment. Corn inbreds B14, B15, and B30, all developed in Iowa, contribute this type of resistance.

Ideally the resistant hybrid should be impervious to leaf feeding by the first generation of borers and tolerant to damage by the second generation. Many corn hybrids contain some degree of each or perhaps both types, but they are commercial hybrids with closed or secret pedigrees. Because we do not know the pedigrees, we have difficulty in determining how widely these inbreds or others developed by private industry are used. We also have trouble measuring their effectiveness in reducing borer damage and popu-

lations in areas infested with this insect. However, both can be estimated to some degree by referring to survey and research data compiled by scientists who are developing inbreds resistant to the corn borer.

In 1949 when all known control practices, both natural (diseases and parasites) and artificial (cultural and insecticides), were in effect to reduce borer populations, the European corn borer caused the heaviest losses, $350 million. Resistant hybrids were not generally used during 1949, and two were grown for the first time on a limited acreage in Ohio. In recent years annual losses have averaged about $100 million (in 1965, $59 million), and the acres planted to resistant corn hybrids have increased to 30 million (1962 estimate compiled with assistance of G. F. Sprague, U.S. Dept. of Agr.). Meanwhile, of course, DDT and other hydrocarbon insecticides developed after World War II for corn borer control have helped reduce losses. However, the amount of resistant corn now being grown and the scientific data available on its effectiveness in reducing damage indicate that using resistant hybrids has been a major factor in this reduction.

In 1959 F. F. Dicke, formerly with the U.S. Department of Agriculture, an international authority on corn borer resistance, determined at Ankeny, Iowa, that hybrids resistant to corn borer attack reduced losses by at least 20 bushels per acre when borer infestations were heavy (fig. 5). An estimated savings of a fourth this amount, or 5 bushels per acre (allowing for less efficient hybrids and spotted or light borer infestations), on the 30 million acres of resistant corn grown in 1962 would amount to a savings of $150 million. Also, the savings for each year since 1962 would be even greater, since the acreage planted to resistant hybrids increases each year.

Growing resistant varieties not only reduces losses in the current year's crop by preventing feeding damage but also indirectly reduces losses in subsequent crops by reducing borer populations. Tests conducted by F. F. Dicke and L. H. Penny of the U.S. Department of Agriculture indicated that growing resistant corn effectively reduced or suppressed borer populations by as much as 50 to 60 percent. The cumulative effect of an annual reduction in population of this magnitude would soon almost eradicate this insect. Apparently this kind of reduction has already taken place in some areas.

In 1956, G. H. Stringfield, an agronomist in Ohio who pioneered in developing resistance to corn borers, stated that the European corn borer had been reduced to minor importance on farms where hybrids with resistance to borer attack were growing. The 1967 corn borer control recommendation listed in the "Suggested Guide for the Use of Insecticides to Control Insects Affecting Field

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FIGURE 5.—European corn borer damage in dent corn at Ankeny, Iowa: Above, susceptible WF9; below, resistant C.I. 31A (WF9 × 458–1).

Corn, Forage, Small Grains, and Soybeans," published by Ohio State University, reads in part as follows: "Prevent damage by selecting resistant hybrids (refer to "Agronomy Guide for Ohio"). Insecticidal treatment in Ohio usually not necessary for level of infestation in field corn. . . ."

T. A. Brindley, U.S. Department of Agriculture, an international authority on the corn borer, stated in an interview by a staff member of the Des Moines Register in 1964 that "we don't have the corn borer losses once common in Iowa . . . because today the farmer is planting improved varieties which are more resistant to the borer. If we had the same kind of corn farmers planted in Iowa back in the early 1950's, this would be a serious infestation . . . now there isn't cause for too much alarm."

Resistance to the corn borer is of primary importance in marketing and selling hybrid seed corn, because seed companies have been forced to develop hybrids that are resistant to borer damage in order to survive in the highly competitive seed corn business. Undoubtedly the three major elements affecting American agriculture—continuing scientific research, competition among growers and seed producers, and desire to increase yields and income—eventually will reduce this most serious pest of corn to one of minor importance throughout the entire corn-growing area of the United States.

## Other Insect Pests

Scientists are also making progress in reducing losses and suppressing populations of other insect pests by developing resistant hybrids and varieties.

W. A. Douglas, U.S. Department of Agriculture, estimated that in Mississippi alone the development of resistant dent corn hybrids—Dixie 18 (yellow), Coker 811 (white), and others—has reduced losses from the corn earworm (*Heliothis zea* (Boddie)) and the rice weevil (*Sitophilus oryzae* (L.)) by $10 million during 1958–68. Damage to dent corn for the entire United States has been estimated at $170 million a year. Much of this loss could probably be prevented by developing and growing resistant hybrids. Many sweet corn inbreds with resistance to attack by the corn earworm have been developed by E. V. Walter, formerly of the Department. These inbreds and others developed by scientists at State experiment stations and in private industry have already been incorporated into some commercial sweet corn hybrids (fig. 6).

In the United States the corn earworm causes an estimated annual loss to sweet corn growers of more than $12 million, even when insecticides are applied for its control. If we add to this amount the estimated cost of chemical sprays and the value of corn forage lost because of chemical residues, the total estimated savings to be realized by using resistant hybrids are more than $17 million annually.

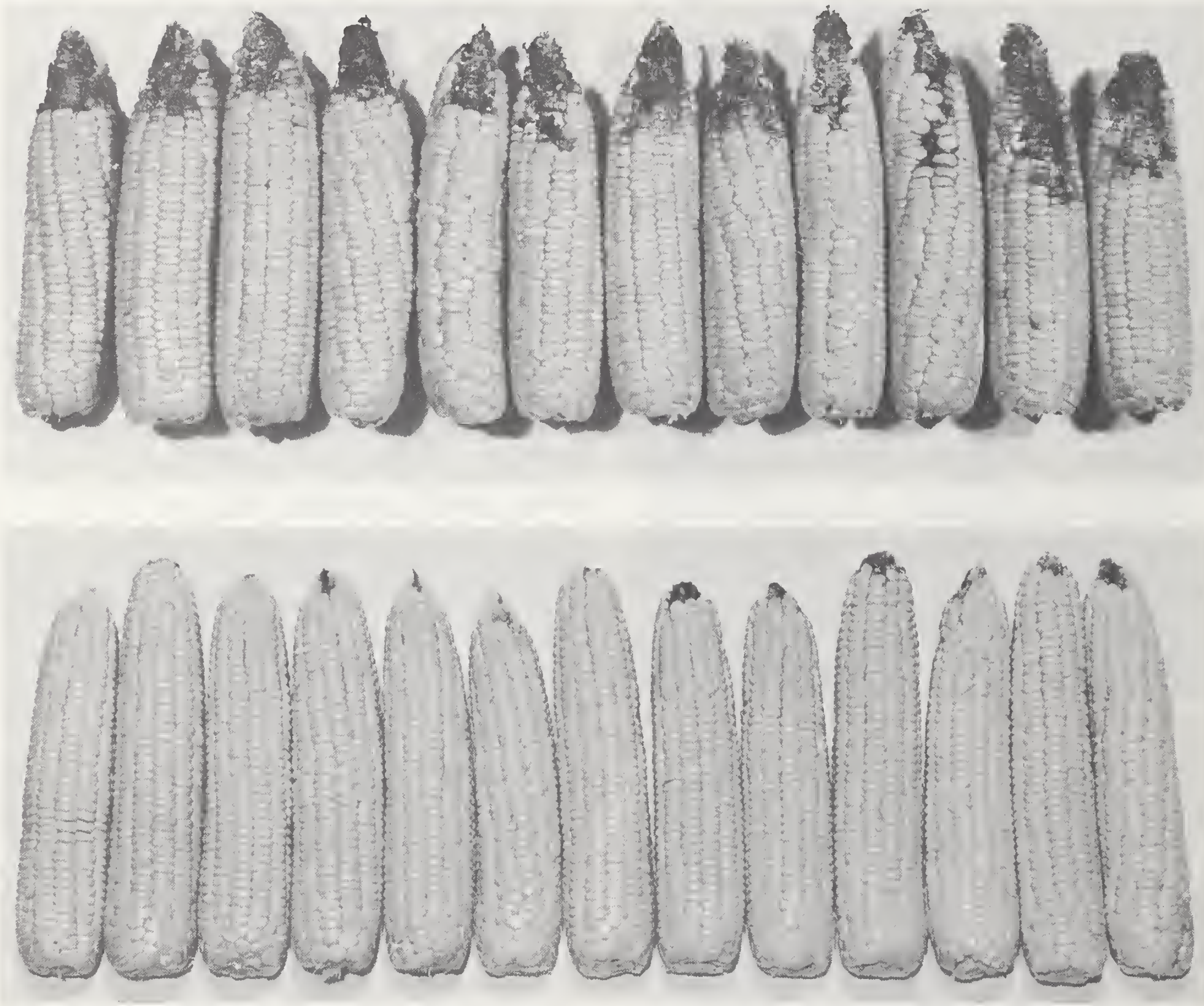
Resistance to insect damage has been built into several crops. Will barley, a variety recently released by Oklahoma State University and the U.S. Department of Agriculture, is resistant to attack by the greenbug (*Schizaphis graminum* (Rondani)) (fig. 7). This variety yields over 50 bushels per acre more than susceptible varieties heavily infested by this insect. The potential savings in grain to the farmer from one such resistant barley alone will therefore be tremendous in years of heavy greenbug populations. Also, wheat varieties resistant to this insect are in advanced stages of development in the breeding program (fig. 8).

For some crops, breeding programs to develop resistant varieties are just starting. The U.S. Department of Agriculture has begun an all-out effort to develop agronomically acceptable cotton varieties with built-in resistance to insects based on scientists' observations that plants without nectar are less attractive than those with nectar to the following insects: Cotton leafworm (*Alabama argillacea* (Hübner)), bollworm (*Heliothis zea* (Boddie)), cabbage looper (*Trichoplusia ni* (Hübner)), pink bollworm (*Pectinophora gossypiella* (Saunders)), and boll weevil (*Anthonomus grandis* (Boheman)) (fig. 9).

Some corn plants are resistant to damage by the corn rootworm (*Diabrotica* spp.) (fig. 10). These plants are being used to develop resistant inbreds and hybrids that can be grown commercially in the infested area. It is hoped that commercial hybrids resistant to rootworms will be available soon, because these beetles are building up resistance to chemical control at an alarming rate.

Researchers are discovering many varieties of commercial sugarcane that are more tolerant than others to attack by the sugarcane borer (*Diatraea saccharalis* (F.)). Growing these varieties will help reduce losses. Scientists are also developing sweetclover varieties resistant to the sweetclover weevil (*Sitona cylindricollis* Fåhraeus) and small grain varieties resistant to the cereal leaf beetle (*Oulema melanopus* (L.)), a pest recently introduced into this country.

Scientists of the U.S. Forest Service have conducted preliminary studies to determine whether some trees are more resistant to insect attack than others. In the Midwest the American elm is commonly infested by the woolly elm aphid (*Eriosoma americanum* (Riley)), and infestations have been observed on the same tree from year to year. Adjoining trees with interlocking limbs are sometimes not infested. The same phenomenon has been observed on Norway spruce infested with the spruce aphid (*Elatobium abietinum* (Walker)). The aphid prefers to infest certain trees rather than others.



BN–34187, BN–34188

FIGURE 6.—Corn earworm damage in sweet corn at Lafayette, Ind. Above, susceptible Golden Cross; below, resistant La2W × 14S.


BN–34189

FIGURE 7.—Greenbug damage in barley at Stillwater, Okla., 1964: Will, resistant; Rogers, susceptible.


BN–34190

FIGURE 8.—Greenbug damage in wheat at Stillwater, Okla.: Left, resistant selection DS28A × Ponca; center, susceptible Ponca; right, resistant DS28A.

BN-34191, BN-34192

**Figure 9.**—Cotton variety Empire (above) completely defoliated by feeding of cotton leafworm under caged conditions at Brownsville, Tex.; nectarless cotton strain (below) undamaged.

Some species of elm are apparently more susceptible to the elm leaf beetle (*Galerucella xanthomelaena* (Schrank)) than others (fig. 11). During the summer of 1965 A. F. Kenyon of Oklahoma State University observed that the Christine Buisman elm tree was nearly defoliated by the elm leaf beetle, but winged, Chinese, and cedar elms suffered little or no damage. The cedar elm also showed resistance to the elm bark beetle (*Hylurgopinus rufipes* (Eichh.)), one of the insect vectors of Dutch elm disease.

In the Midwest the locust borer (*Megacyllene robiniae* (Forster)) is destructive on black locust. However, certain stands of this tree, even in a generally infested area, suffer little damage. The reason some trees remain undamaged could very well be because of natural immunity to the locust borer.

BN–34193

FIGURE 10.—Corn rootworm damage in sweet corn at Lafayette, Ind.: Texas inbred 5014–5–1–1 (leaning) and Texas inbred 5014–2–1–1 (standing), apparently resistant.

BN–34194, BN–34195

FIGURE 11.—Christine Buisman elm tree (left) nearly defoliated by elm leaf beetle at Stillwater, Okla.; winged elm tree (right) in same field shows little or no damage.

C. H. Brett of North Carolina State University found that some vegetable varieties are more resistant to insect feeding than others. The snap bean variety Wade, for example, is more resistant to damage by the Mexican bean beetle (*Epilachna varivestis* Mulsant) than the variety Bountiful (fig. 12). The summer crookneck squash is more resistant to the pickleworm (*Diaphania nitidalis* (Stoll)) than the squash variety Benning Green Tint Scallop (fig. 13).

BN–34196, BN–34197

FIGURE 12.—Bountiful snap bean (left), susceptible to Mexican bean beetle; Wade (right), resistant. (Courtesy of C. H. Brett, N.C. State University.)

BN–34198, BN–34199

FIGURE 13.—Benning Green Tint Scallop squash (left), susceptible; summer crookneck squash (right), resistant to pickleworm. (Courtesy of C. H. Brett, N.C. State University.)

## Discussion

Let us consider the total estimated value of the research on resistant plants compared to its cost for four of the insects discussed. About 115 professional man-years for the Hessian fly, 92 for the sawfly, 119 for the alfalfa aphid, and 136 for the corn borer have cost about $20,000 a man-year for salary and other expenses, totaling $9.3 million. Federal, State, and private agencies have invested this amount to develop resistant varieties for these four insect pests. The savings to the farmer are about $308 million a year. After a variety or inbred is developed, it is usually grown successfully for about 10 years before it is discarded for biological, agronomic, or other reasons. Thus the cost of research ($9.3 million), the annual savings ($308 million), and the 10 years' use of a variety give a total net monetary value of about $3 billion, a 300:1 return for each research dollar invested. This cost, of course, is based only on preventing damage and yield loss. The estimated value of the bonus effects—eradication or suppression of insect populations and elimination of chemical sprays and residues—is not included.

Research dealing with the resistance of host plants to attack by insects is a challenging new frontier of science. With proper research, many major insect pests causing economic damage to crops will probably be controlled by using multiresistant varieties, perhaps by the end of the century.

To accomplish this, much basic and applied research must be conducted (1) to find new sources of insect-resistant germ plasm in plants and build this resistance into agronomically acceptable plants; (2) to combine the insect-resistant germ plasms for the different insect species into the same crop plant; (3) to study insect biotypes; and (4) to learn more about the nature of plant resistance.

Developing plants with resistance to insect attack is a slow process. Ten years or more are usually required to develop a variety with resistance to a single insect species and probably twice as long for varieties resistant to two or more species. Building multiresistance to pests into our many cultivated crops is not simple. To succeed, entomologists, agronomists, pathologists, geneticists, and others must work together as a research team.

Resistance to pests exists throughout nature. It is all around us in animals and plants. It needs only to be discovered, identified, and put to work to solve many of our most serious pest problems.

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